1 Abstract

1.1 Introduction

Commercial fishing plays a vital role in the global food chain, providing a source of food for millions of people around the world. However, with technological progress and population growth, fisheries face numerous challenges and difficulties that have a significant impact on the sustainable management of fish resources (Godfray et al. 2010). The fishing industry faces several problems that threaten marine life, the environment, and the economy (Hilborn et al. 2003). Overfishing can cause a decline not only in fish populations (Myers and Worm 2003), but also lead to starvation of fish-eating birds (Camphuysen and Garthe 2000), which can have ripple effects throughout the ecosystem. At the same time, it should be remembered that fishing is driven by living people (fishers), for whom it is often the only source of income. Regulations aimed at protecting declining or endangered species and the environment make day-to-day fishing less and less profitable.

Trying to help overcome these problems, we decided to implement the project called *"Knowledge Transfer Platform FindFISH – Numerical Forecasting System for the Marine Environment of the Gulf of Gdańsk for Fisheries"* (Lidia Dzierzbicka-Głowacka et al. 2018; L. Dzierzbicka-Głowacka 2023). The aim of *FindFISH* is to deal with the declining profitability of commercial fisheries, by reducing fishing time (fuel saving) and thus prevent environmental pollution. Our numerical modeling approach will enable fishers to optimize their catch and avoid bycatch. The result of the project is a user-friendly web service (www.findfish.pl) that provides accessible information regarding the physical and biochemical state of the Gulf of Gdańsk in the form of 48-hour forecasts.

One of the key components of this system is the *"Fish Module"* - algorithm designed to generate maps of the Habitat Suitability Index (HSI), indicating the locations of the best environmental conditions for fish in the Gulf of Gdańsk. It is implemented for four species: sprat (*Sprattus sprattus*), herring (*Clupea harengus*), cod (*Gadus morhua*), and flounder (*Platichthys flesus*). We expect the *Fish Module* to be the most demanded product of the *FindFISH* service.

The research conducted as part of this doctoral thesis confirmed the main research hypothesis, which posited that **it is possible to determine optimal environmental conditions for the habitat of selected fish species occurring in the southern Baltic Sea region (particularly in the Gulf of Gdańsk) by using numerical modeling**.

Four specific objectives were established to confirm the research hypothesis:

1. Characterize the structure and variability of hydrodynamic parameters in the Gulf of Gdańsk region.

2. Investigate the vertical structure of water in the Gulf of Gdańsk region with a precise determination of the thermocline and halocline, which act as barriers to fish migration.

3. Characterize the structure and variability of biochemical parameters in the Gulf of Gdańsk, and the influence of limiting factors on the primary production of phytoplankton.

4. Apply numerical modeling to identify areas where optimal conditions for the habitat of sprat, herring, cod, and flounder occur in the Gulf of Gdańsk region, based on the environmental preferences of these species.

Each of the specific objectives mentioned above has been discussed in a separate scientific articles, and their compilation forms the subject of this dissertation.

This doctoral dissertation consists of three published scientific papers in peer-reviewed journals and a manuscript attached at the end of the dissertation, which was submitted to the journal and is a consistent continuation of the research undertaken in the previous three papers.

The first paper (Janecki, Dybowski, Jakacki, et al. 2021) focuses on the description and validation of the hydrodynamic component of the *EcoFish* model. The second paper (Janecki, Dybowski, Rak, et al. 2022) presents an innovative method for determining the top depths of the thermocline and halocline. The third paper (Janecki, Dybowski, and Lidia Dzierzbicka-Głowacka 2023) presents and validates the biochemical component of the *EcoFis*h model and investigates how limiting factors influence the nature and intensity of primary production of phytoplankton. The fourth manuscript (Janecki and Lidia Dzierzbicka-Głowacka 2023) is dedicated to the *Fish Module*, which utilizes fuzzy logic to create maps of the most favorable environmental conditions (Habitat Suitability Index - HSI) for commercially harvested fish species in the Gulf of Gdańsk region, namely

herring, sprat, cod (until 2021), and flounder. The largest part of the manuscript is devoted to the analysis of data from fishing expeditions and the validation of the results obtained from the *Fish Module* by comparing HSI values with catch efficiencies from fishing expeditions conducted during the project. The *Fish Module* utilizes data from the *EcoFish* model to calculate HSI score.

1.2 Material and methods

1.2.1 Model EcoFish

The *EcoFish* model is based on the source code of the Community Earth System Model (CESM), a global coupled climate model. CESM consists of five separate components with an additional module controlling time, forcing , domains, grids, and information exchange between the individual modules. Within the *FindFISH* project, CESM was downscaled and adapted for the Gulf of Gdańsk region. The horizontal resolution of the *EcoFish* model is 575 meters, and vertically it is a *z-type* model with 26 levels, each with a thickness of 5 meters. The *EcoFish* model comprises two active (performing numerical simulations) parts: the hydrodynamic and the biochemical components.

The hydrodynamic component is an ocean model, based on the source code of the Parallel Ocean Program (POP), which utilizes three-dimensional motion equations with hydrostatic and Boussinesq approximations.

The biochemical component of *EcoFish* is based on an NPZD-type model (Moore et al. 2001). The model determines the concentrations of nutrients, three types of phytoplankton (diatoms, small phytoplankton, and diazotrophs capable of directly fixing atmospheric nitrogen), chlorophyll *a*, microzooplankton, pelagic detritus, and dissolved oxygen concentration.

1.2.2 Fish Module

The *Fish Module* is a computer algorithm that constitutes the final element of the *Knowledge Transfer Platform FindFISH*. Using expert knowledge and data on water temperature, salinity, oxygen saturation, fishing depth, and catch composition and weight, we were able to determine the optimal conditions for the habitat of four commercially fished species in the Gulf of Gdańsk region. These species are herring, sprat, cod (until 2021), and flounder. Subsequently, fuzzy rules were established that connect the input variables to the preferences of each species. This fuzzy system uses the *EcoFish* model data to determine the Habitat Suitability Index (HSI) for the Gulf of Gdańsk region. The HSI indicates the habitat conditions in the studied area. The HSI score ranges from 0 to 1, where 0 indicates that the habitat does not meet the conditions for the occurrence of a particular specie, while 1 describes a habitat with optimal conditions.

The determination of membership functions in the *Fish Module* involved the utilization of data defining the ranges of preferable values for each parameter governing the habitat of sprat, herring, cod, and flounder. These ranges were established based on physicochemical data (temperature, salinity, oxygen saturation, and fishing depth) and fishing data (catch composition and weight) collected during fishing expeditions.

The median of the optimal value was implemented along with a constant deviation C, and the minimum/maximum at the edges. The preferences of each species implemented in the *Fish Module* were fuzzified in a way that the central trapezoid encompassed the optimal values of the respective parameter for the species' habitat, while lower and higher values represented conditions below and above the optimal range, respectively.

1.2.3 Study area

The effective domain of the *EcoFish* model includes the extended Gulf of Gdańsk, which is the southern part of the Gdańsk Deep area, located in the Gotland Basin. A straight line connecting Cape Rozewie with Cape Taran delimits the proper Gulf of Gdańsk. This line crosses the deepest parts of the Gdańsk Deep, with a maximum depth of 118 meters. Along the coastal zone there is a wide strip of shallows widening to the west of the mouth of the Vistula River. The slope of the bottom in the coastal zone is varied. The greatest decline occurs at the headland of the Hel Peninsula, where the bottom rapidly drops to a depth of 70 meters (Majewski 1972).

1.3 Results and discussion

In this chapter, the most important results of the research are presented, while the individual results and analyzes are presented in the articles that constitute this doctoral dissertation.

1.3.1 Hydrodynamic part of the EcoFish model

The validation showed that the *EcoFish* model results for water temperature were consistent with *in situ* observations. The correlation of the *EcoFish* model with ICES data was 0.94 with the root mean square error (RMSE) of 1.33 °C. As a result of comparing the modeled temperature against the data from the database created during fishing cruises, a correlation coefficient of 0.87 was calculated. This is a satisfactory result, taking into account, the strong concentration of cruise data in the belt from the mouth of the Vistula River in the northwest direction. Thus, the data come both from the area where there is mixing of river waters (from the Vistula River) with the waters of the Gulf and from the area where the strongest currents occur in the entire domain (the belt along the Hel Peninsula).

The correlation of the model results for salinity with the ICES data at the level of 0.94 and the low root mean square error of 0.8 PSU suggest that the model copes well with the transport of water masses. It also proves that the rivers in the model have been correctly implemented and that the outgoing freshwater is correctly mixed with the saltwater of the Gulf and distributed by currents in its area.

1.3.2 Algorithm for determining the top of the thermocline and halocline depths

The second article (Janecki, Dybowski, Rak, et al. 2022) presents an innovative method called the *"MovSTD Algorithm"* for determining the top of the thermocline (TTD) and halocline (THD) depths. The method has been calibrated using an extensive set of data from the *EcoFish* model. As a result of the calibration, the values of the input parameters that allowed the correct determination of TTD and THD were established. It was confirmed by the validation carried out on the *in situ* profiles collected by the research vessel S/Y Oceania during statutory cruises in the southern Baltic Sea. The *MovSTD* algorithm was then used to analyze the seasonal variability of the vertical structure of the waters in Gdańsk Deep for temperature and salinity. The thermocline deepening speed was also estimated in the region analyzed.

The motivation behind addressing this topic was the association between the thermocline and the occurrence of fish. In some cases, the thermocline can act as a barrier to fish movement, as they prefer specific temperature ranges. In such cases, fish may gather at the thermocline boundary where suitable habitat conditions are available. Therefore, knowledge of the thermocline depth can help determine where the presence of certain fish species can be expected.

The results from the *MovSTD* algorithm when tested on model data from the Gdańsk Deep region showed that the top of the halocline depth is permanent and is located at about 50 m. Noticeable changes in the depth of the halocline can be observed in the 7-yr period analyzed. From August to November, the THD begins to form higher, at depths between 35 and 50 m. In addition, between January and February 2015 and 2016 it reached instantaneous values of 70 m deep. However, it can be said that THD does not show significant seasonal variability and the vertical structure of salinity in the Gdańsk Deep is rather stable.

The situation is different for the thermocline. We can observe a strong seasonal variability here. A fresh thermocline begins to form in May due to the heating of the surface layer (forced by air temperature and sunlight). Its deepening speed from May to September is about 2 m per month. In the following months, as a result of water mixing and increased wind forcing, the thermocline deepening accelerates, reaching greater depths at a speed of about 9 m per month. At the turn of the year, this process stops, and until April thermocline occurs at the same depth as the halocline.

1.3.3 Biochemical part of the EcoFish model

The third article (Janecki, Dybowski, and Lidia Dzierzbicka-Głowacka 2023) presented the biochemical component of the *EcoFish* model for the Gulf of Gdańsk region. The basic parameters of the marine ecosystem were determined, including the concentration of chlorophyll *a*, dissolved oxygen, and concentration of nutrients as nitrate, phosphate, and silicate. The seasonal variability of these parameters was presented, and the model data was validated by comparing it with *in situ* data from the ICES database, yielding satisfactory results.

The article also examined how limiting factors (i.e., water temperature, nutrients, light) influence the primary production of phytoplankton and demonstrated that the intensity of spring diatom blooms affects the nature of cyanobacterial blooms in the summer. The analysis of the seasonal dynamics of primary production in the waters of the Gulf of Gdańsk was crucial for the conducted research, as this process is directly linked to oxygen production and consumption. In the analysis of primary production, it was shown that geomorphological conditions and the deposition of nutrients from rivers significantly influence its character and intensity. The availability of biogenic substances can significantly alter the biomass distribution of all phytoplankton groups. An excessive reduction in nitrate deposition in river waters aimed at mitigating marine eutrophication may, consequently, lead to a situation where short and weak diatom blooms occur in spring, followed by long and intense cyanobacterial blooms in summer.

1.3.4 Mapping the optimal environmental conditions for the habitat of sprat, herring, cod, and flounder in the Gulf of Gdańsk region

Janecki and Lidia Dzierzbicka-Głowacka 2023 is the final article that utilizes the knowledge and results obtained in the previous three published works. It focuses on the *Fish Module*, which is the most important element of the Knowledge Transfer Platform *FindFISH*. Using fuzzy logic, the *Fish Module* enables the creation of maps depicting the most favorable environmental conditions (HSI - Habitat Suitability Index) for the habitats of commercially harvested fish species in the Gulf of Gdańsk region.

By calculating the mean HSI values for all the analyzed fishing expeditions and species and comparing them with fishing efficiencies, it was observed that there is a threshold HSI value below which successful catches are unlikely to occur for sprat, herring, and cod. This indicates the system's accuracy in identifying locations with favorable environmental conditions for the habitat of these three species. Fishermen are advised to select routes where the HSI is at least 0.5 for herring and sprat, and greater than 0.4 for cod. Furthermore, a slight trend was observed for these three species, indicating an increase in fishing efficiency with higher HSI values. This shows that selecting routes with sufficiently high HSI values contributes to achieving higher fishing efficiencies.

Regarding flounder, the assessment based on comparing fishing efficiency with the mean HSI from the gillnet deployment position did not provide conclusive evidence regarding the system's ability to accurately identify locations with optimal environmental conditions for this species. Although there was a substantial amount of flounder data available, its spatial coverage was not as extensive as that of sprat or herring. The nets were deployed only within three specific areas: the southern part of the Gulf of Gdańsk, the vicinity of the Vistula Spit, and both sides of the Hel Peninsula.

1.4 Summary

The application of modern measurement techniques and numerical modeling within the *FindFISH* project allowed for the determination of optimal environmental conditions for the habitats of herring, sprat, cod, and flounder in the Gulf of Gdańsk region. The development of the *Fish Module* and the availability of HSI map forecasts through an online portal can lead to more selective fishing practices and cost reductions for the fishing industry.

The implementation of the *FindFISH* platform enables the diagnosis and forecasting of marine environmental conditions in the Gulf of Gdańsk, facilitating quick access to necessary information. This can result in the reduction of unwanted catches through informed fishing location selection based on specific numerical results presented in a transparent and comprehensible format.

References (Bibliografia)

Camphuysen, C.J. and S. Garthe (2000). "Sea birds and commercial fisheries: population trends of piscivorous seabirds explained?" In: *Effects of Fishing on Non-Target Species and Habitats*. Oxford: Blackwell Science, pp. 163–184.

Dzierzbicka-Głowacka, L. (2023). *Platforma transferu wiedzy FindFISH – Numeryczny System Prognozowania warunków środowiska morskiego Zatoki Gdańskiej dla Rybołówstwa*. pl. Gdynia: Wydawnictwo Uniwersytetu Morskiego w Gdyni. ISBN: 978-83-7421-447-6. URL: https://doi.org/10.26408/FindFISH.

Dzierzbicka-Głowacka, Lidia et al. (2018). "Structure of the FindFish Knowledge Transfer Platform". pl. In: *Fisheries & Aquatic Life* 26.3, pp. 193–197. DOI: 10.2478/aopf-2018-0021.

Godfray, H. Charles J. et al. (2010). "Food Security: The Challenge of Feeding 9 Billion People". In: *Science* 327.5967, pp. 812–818. DOI: 10.1126/science.1185383.

Hilborn, Ray et al. (2003). "State of the World's Fisheries". In: *Annual Review of Environment and Resources* 28.1, pp. 359–399. DOI: 10.1146/annurev.energy.28.050302.105509.

Janecki, Maciej, Dawid Dybowski, and Lidia Dzierzbicka-Głowacka (2023). "The influence of biochemical parameters on primary production in the Gulf of Gdańsk region: A model study". en. In: *Oceanologia*. ISSN: 0078-3234. DOI: 10.1016/j.oceano.2023.05.001.

Janecki, Maciej, Dawid Dybowski, Jaromir Jakacki, et al. (2021). "The Use of Satellite Data to Determine the Changes of Hydrodynamic Parameters in the Gulf of Gdańsk via EcoFish Model". en. In: *Remote Sensing* 13.18, p. 3572. ISSN: 2072-4292. DOI: 10.3390/rs13183572.

Janecki, Maciej, Dawid Dybowski, Daniel Rak, et al. (2022). "A New Method for Thermocline and Halocline Depth Determination at Shallow Seas". EN. In: *Journal of Physical Oceanography* 52.9, pp. 2205–2218. ISSN: 0022-3670, 1520-0485. DOI: 10.1175/JPO-D-22-0008.1.

Janecki, Maciej and Lidia Dzierzbicka-Głowacka (2023). "Fish Module - A Prognostic Tool for Modeling the Optimal Environmental Conditions for Fish in the Gulf of Gdańsk (Southern Baltic Sea)". In: *submitted to Fish and Fisheries Journal*.

Majewski, A. (1972). "Hydrological characteristics of estuarine waters at the Polish Coast". pl. In: *Prace Panstw. Inst. Hydrol.- Meteorol.* 105, pp. 3–40.

Moore, J. Keith et al. (2001). "An intermediate complexity marine ecosystem model for the global domain". en. In: *Deep Sea Research Part II: Topical Studies in Oceanography*. The US JGOFS Synthesis and Modeling Project: Phase 1 49.1, pp. 403–462. ISSN: 0967-0645. DOI: 10.1016/S0967-0645(01)00108-4.

Myers, Ransom A. and Boris Worm (2003). "Rapid worldwide depletion of predatory fish communities". en. In: *Nature* 423.6937, pp. 280–283. ISSN: 1476-4687. DOI: 10.1038/nature01610.